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ORIGINAL ARTICLE

Using Superconducting Magnet to Reproduce Quick Variations of Gravity in Liquid Oxygen

Guillaume Pichavant · Daniel Beysens · Denis Chatain · Daniel Communal · Clément Lorin · Alain Mailfert

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Abstract A ground based facility (OLGA), providing magnetic compensation of gravity in oxygen, has been developed. A 2-T superconducting magnetic solenoid is used to create the required magnetic field. A novel electrical supply permits to quickly vary the magnetic field, leading to rapid variation of the acceleration forces applied to oxygen. These variations can be made from overcompensation of gravity ($-0.5g$) to zero gravity or from zero gravity to reduced gravity ($0.4g$) with a time constant of 340 ms. This time is typical of the cutoff or reignition of spacecraft engines. Preliminary results on the transient flows induced by these acceleration variations in a reservoir filled with liquid and gaseous oxygen are presented.

Keywords Microgravity · Magnetic levitation · Magnetic compensation · Oxygen · Time-varying compensation

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G. Pichavant · D. Beysens · D. Chatain (✉) · D. Communal
ESEME, Service des Basses Températures, CEA-Grenoble/DSM/INAC, 17 rue des Martyrs, 38054, Grenoble Cedex 9, France
e-mail: denis.chatain@cea.fr

D. Beysens
CEA-ESEME, ESPCI-PMMH, 10 rue Vauquelin, 75251, Paris Cedex 5, France

C. Lorin · A. Mailfert
LEM, UMR CNRS n°7569, INPL, Nancy Université, 2 avenue de la Forêt de Haye, 54516 Vandoeuvre, France

Introduction

Several means can be used to obtain a reduced gravity environment (free fall tower, zero-G plane, sounding rockets, satellites as the International Space Station). However, the time of microgravity, the cost of the flight ticket or the availability of the platform can be penalizing. Magnetic compensation using superconducting materials can theoretically give an infinite time for experiments (Nikolayev et al. 2010). The OLGA (Oxygen Low Gravity Apparatus) facility has been developed at CEA/Grenoble to provide an opportunity to study the oxygen gas and liquid behavior under variable effective gravity, g': from zero gravity ($0g$) to earth gravity ($1g$). Typical values encountered in rockets are the following: shut-down, from 0.3 to $0g$ in 1 s; pre-reignition, from 0 to $0.002g$ in 10 ms then ignition for 10 to 500 s.

A number of key phenomena occurring during the utilization of spacecrafts, such as cryogenic engine cooling before ignition, fuel sloshing in reservoirs, etc. can thus be studied in a ground-based facility (Pichavant et al. 2009). OLGA indeed provides a magnetic compensation of gravity of liquid and gas (and solid) oxygen in a few cubic centimeters volume. OLGA is the follow-up of a general concept that started with the magnetic compensation of gravity in solid bodies (Beaugnon and Tournier 1991; Kitamura et al. 2000) and fluids such as helium (Weilert et al. 1996), hydrogen (Wunenburger et al. 2000; Chatain and Nikolayev 2002; Nikolayev et al. 2006) or oxygen (Lyon et al. 1965).

Principle of Magnetic Compensation

In the influence area of a magnetic field, paramagnetic (e.g. oxygen) and diamagnetic (e.g. hydrogen)

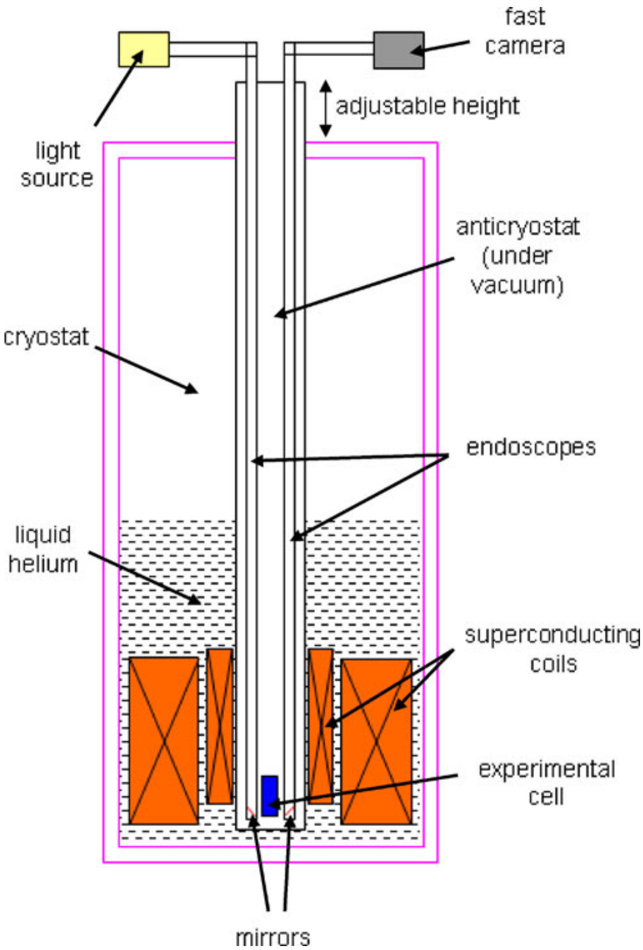

Fig. 1 Schematic view of the OLGA facility

materials are subjected to a volume force $F_{magnetic} = (\chi/(2\mu_0))\overrightarrow{grad}(B^2)$ where χ is the magnetic susceptibility of the considered material, μ_0 is the vacuum magnetic permeability and B is the applied magnetic field. In order to compensate gravity in oxygen, the value of $grad(B^2)$ needs to be 8.15 T^2/m at 90.1 K.

This force is proportional to density, like weight. Then the compensation of gravity occurs independently of the state of matter (liquid, gas or solid). The advantages of such a technology are obvious: reduced gravity time potentially infinite, adjustable gravity level and use of dangerous substances (oxygen, hydrogen).

The main drawback stays in the fact that the residual gravity field can not be perfectly homogeneous (Quettier et al. 2005).

Presentation of the Facility

Cryostat

OLGA is a cryogenic facility (Fig. 1). The cryostat contains two coaxial cylindrical solenoids made of Nb–Ti superconductive alloy, cooled with liquid helium at 4.2 K. The external solenoid is 555 mm high with 434 mm internal diameter and 650 mm external diameter. The internal solenoid is 570 mm high with 336 mm inner diameter and 406 mm outer diameter. The presence of truss rods and mechanical assembly elements limits the useful bore to 320 mm. The inductance of the external solenoid is 5.07 H and that of the internal solenoid is 0.17 H.

To compensate gravity in O_2 at 90.1 K, either the external solenoid is used alone with a current of $I_e =$ 239.25 A, or both solenoids are used together with a current of $I_e = 186.6$ A in the external coil and $I_i =$ 170 A in the internal coil. The quality of compensation in the OLGA facility can be deduced from the magnetic field map as shown in Pichavant et al. (2009) or resulting magnetic forces from Nikolayev et al. (2010).

In order to illustrate the aspect of a gas–liquid interface during compensation of gravity in both cases, one can have a look at the Fig. 2a (picture $t_0 + 1.4$ s) and the

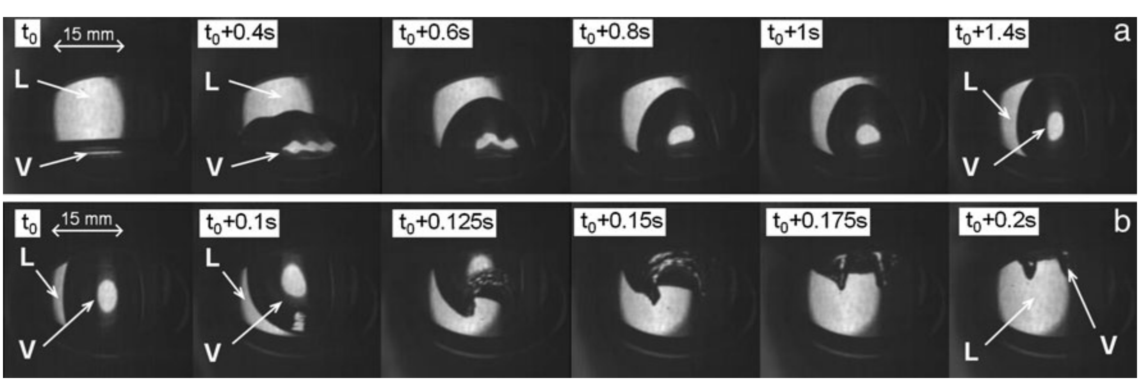

Fig. 2 **a** Time evolution of the interface shape during a transition from −0.5 to 0*g*. **b** Time evolution of the interface shape during a transition from 0 to 0.4*g*. *L* the liquid phase, *V* the vapour phase

Fig. 2b (picture t_0): the typical spherical shape of a vapor bubble in microgravity is clearly visible. The vapour bubble is, however, slightly deformed by an instability (Cowley and Rosensweig 1967). It is due to the fact that any density heterogeneity, in particular, the liquid–gas interface, can cause a magnetic field distortion whose amplitude is proportional to χ and is thus larger for O_2 than for diamagnetic fluids. This distortion leads to a coupling of the magnetic field and interface shape. Therefore O_2 exhibits a behavior similar to that of ferrofluids (i.e. colloidal suspensions of ferromagnetic particles) because, similarly to ferrofluids, the sign of χ for oxygen is positive. The gas–liquid interface of such fluids becomes unstable with respect to a small interface deformation when B exceeds a threshold B_S that varies as $l_c^{-1/2}$, where $l_c = [\sigma/(g\Delta\rho)]^{1/2}$ is the capillary length (σ is the vapor–liquid surface tension and $\Delta\rho$ is the density difference between the liquid and vapor phases). The instability creates a corrugation of the interface, whose period is $\lambda = l_c/2\pi$, as seen in Catherall et al. (2005). Usually, it is observed in O_2 only under high magnetic fields ($B > 2$ T). Under the OLGA magnetic field, B ($\sim$1.5 T) $< B_S$, and the effect resumes in only a slight deformation of the bubble shape.

Anticryostat

An anticryostat is placed inside the cryostat through the solenoids. It contains the experimental cell and a visualisation system. Thanks to two endoscopes and their corresponding mirrors (for light source and camera), magnetic and temperature effects on the visualisation device can be avoided. The anticryostat is mobile and its vertical position with respect to the cryostat and the solenoids is adjustable. Both endoscopes are mobile with respect to the anticryostat and can move independently. Their mirrors can rotate to adjust the field of view.

Principle

A fast variation of the magnetic force from a certain level of gravity to another is possible by using two solenoids: one solenoid (internal) must have his current, I_i, set to zero as fast as possible whereas the other (external), I_e, must keep constant.

For this reason, the electrical circuit of the internal solenoid is opened by a switch that isolates it from its electrical supply. The energy contained in the solenoid is then discharged into an outside dump resistor following an exponential relaxation with a time constant of 340 ms. Due to the electromagnetic coupling, the external coil current can not stay stable naturally and a voltage appears at its edges. A specific electrical supply has thus been designed to deliver an opposite voltage to the external coil at the same time so as to keep its current stable during the transition. The experimental tests lead indeed to a time variation of the external coil current and corresponding gravity acceleration with the expected time constant of 340 ms (Fig. 3).

Experimental Cell

The experiments are performed in a cylindrical cell (Fig. 4). The (transparent) sapphire cylinder (30 mm diameter and 100 mm long) is closed by two copper flanges. They both contain a heat exchanger that serves to regulate the cell temperature. Several thermistors (cernox, specially designed to be used in a magnetic field) placed in the flanges of the cell measure the local temperature.

Procedure

The oxygen, taken from a gas bottle of 5.8 purity (99.9998%), was condensed into the cell at 90.1 K. When the cell was filled within about 80%, the current corresponding to the compensation of gravity (239.25 A) was applied in the external solenoid and the

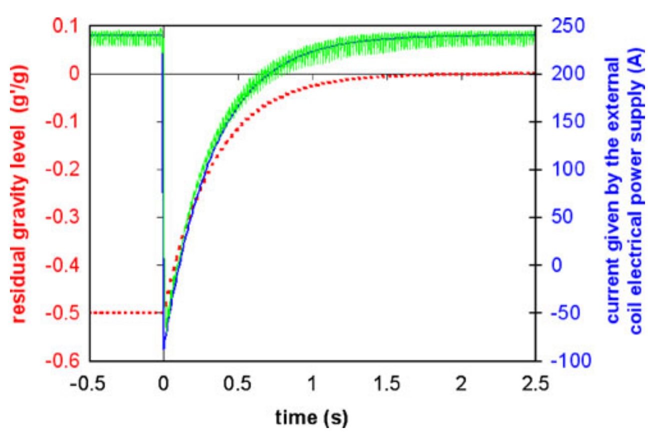

Fig. 3 Theoretical exponential response (*full curve*) of the current provided to the external coil so as to keep I_e constant and its experimental value (*oscillating curve*, *right ordinate*) Oscillations on the experimental curve are due to the measurement system. The reduced effective gravity level (g'/g) as deduced from the magnetic force is shown (*dotted line*, *left ordinate*). It corresponds to an exponential variation from -0.5 to $0g$

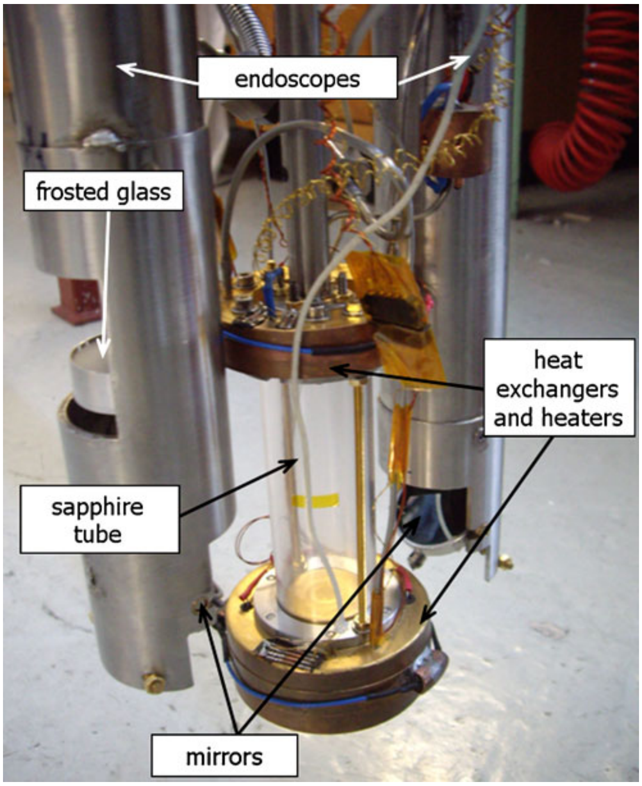

Fig. 4 Photograph of the experimental cell

liquid–vapor interface slowly transformed into a near-spherical bubble (see picture $t_0 + 1.4$ s in Fig. 2a). As discussed above, the bubble cannot be ideally spherical as some residual gravity forces remain. The bubble size was adjusted with the pressure in the cell. Eventually, the currents in the internal and the external solenoids were set to the desired initial values.

The experiments were isothermal. O_2 was kept at a temperature of 90.1 K during the experiments. The incident light was made diffuse by sending a parallel light beam to a frosted glass in front of the cell. Video movies were performed at 500 frames per second. Some pictures have been extracted from the movies (Fig. 2a, b). The experiments were very reproducible.

It is useful to express the results in terms of the classical non-dimensional number: Bond number (gravity versus surface tension forces): $\mathrm{Bo} = \Delta\rho g' L^2/\sigma$; Ohnesorge number (viscous versus inertial and surface tension forces): $\mathrm{Oh} = \mu_L/(\sigma\rho_L L)^{1/2}$; Weber number (inertial versus surface tension forces: $\mathrm{We} = \rho_L v^2 L/\sigma$; Reynolds number (inertial versus viscous forces): $\mathrm{Re} = (\rho_L v L/\mu_L)$. The values during the transitions are given in Table 1 using the following values at 90.1 K at 1.004 bar: liquid (subscript L) and vapor (subscript V) densities $\rho_L = 1{,}142$ kg·m^{-3}; $\rho_V = 4.430$ kg·m^{-3}; L and V shear viscosities $\mu_L = 1.963 \times 10^{-4}$ Pa·s; $\mu_V = 7.007 \times 10^{-6}$ Pa·s; L–V surface tension $\sigma = 1.320 \times 10^{-2}$ N·m^{-1}.

Table 1 Characteristic numbers during the transition

$-0.5/0g$	$0/0.4g$
$g' \sim 10^{-2}$ m·s^{-2}	$g' = 3.92$ m·s^{-2}
$L \sim 10^{-2}$ m (bubble radius)	$L \sim 10^{-2}$ m (bubble radius)
$v \sim 10^{-2}$ m·s^{-1} (interface speed)	$v \sim 10^{-1}$ m·s^{-1} (bubble speed)
Bo $\sim 10^{-1}$ Oh $\sim 10^{-3}$ We $\sim 10^{-1}$; Re $\sim 10^3$	Bo ~ 10 Oh $\sim 10^{-3}$ We ~ 10; Re $\sim 10^4$

Transition from -0.5 to $0g$ (deceleration)

The current variation in the external solenoid has been measured (Fig. 5a). Its variation remains below 0.4% of its initial value, in contrast, the internal solenoid current varies from 170 to 0 A.

In Fig. 2a, initially (at time t_0), the liquid–vapor interface is flat: the vapor phase is located below the liquid phase (negative gravity). The vapor phase gradually

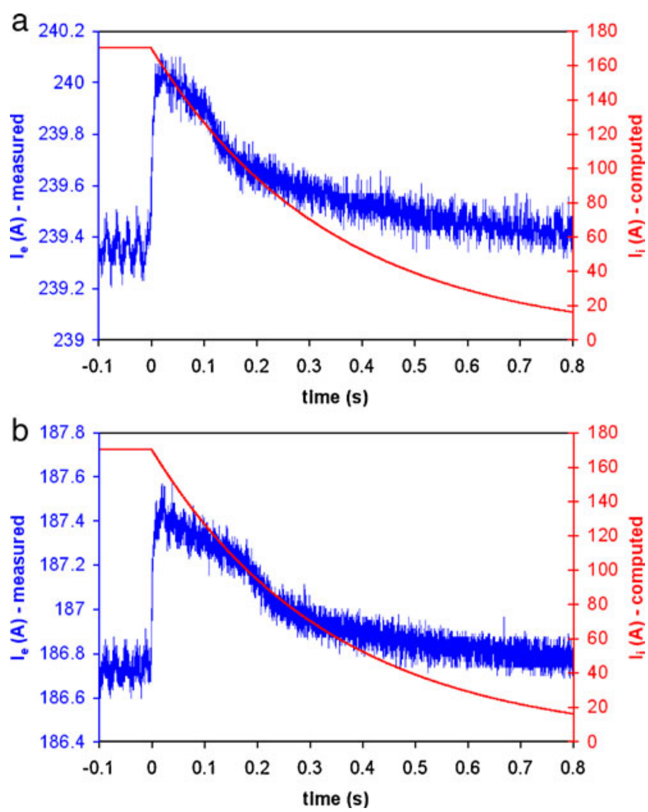

Fig. 5 **a** Current measured in the external coil (I_e, *left ordinate*) and calculated current in the internal coil (I_i, *right ordinate*) during a -0.5 to $0g$ transition. **b** Current measured in the external coil (I_e, *left ordinate*) and calculated current in the internal coil (I_i, *right ordinate*) during a 0 to $0.4g$ transition

gets the typical round shape under microgravity during the transition. Instabilities are visible on the interface at $t_0 + 0.4$ s and $t_0 + 0.6$ s. From Table 1, it is clear that inertial and capillary phenomena dominate the process.

Transition from 0 to 0.4g (acceleration)

In Fig. 5b, the variation of I_e in the external coil remains below 0.4% during the transition, in contrast to the variation of the internal solenoid current that simultaneously decreases from 170 to 0 A.

In Fig. 2b, initially (at time t_0), the vapour bubble is in a microgravity state (typical near-round shape). The current in the external solenoid is $I_e = 186.6$ A; it is $I_i = 170$ A in the internal coil.

As soon as gravity increases, the bubble begins to move upwards because of the buoyancy force. The liquid flows down along the cell walls and meet down in the middle of the cell where it forms a jet that penetrates the bubble. The jet is visible after $t_o + 0.125$ s. In addition the liquid–vapor interface is deformed by Kelvin–Helmotz interface instabilities (Baumbach et al. 2005). From Table 1 one deduces that gravity and inertial forces control the process.

Conclusion

The magnetic compensation facility OLGA enables fast variations of acceleration to be performed in a O_2 gas–liquid sample cell. Not only can different levels of gravity be produced, from ground conditions (1g) to space conditions (0g), but also fast variations of acceleration (340 ms time constant) can be performed. As a consequence, OLGA gives the unique opportunity to study physical phenomena under time dependent gravity. In particular, configurations that correspond in spacecraft engines to a cutoff (−0.5 to 0g) or a reignition (0 to 0.4g) can be reproduced on earth. More configurations are possible by simply modifying the initial currents in the solenoids.

The results obtained confirmed the efficiency of the magnetic compensation not only to create on the ground different levels of gravity and microgravity, but also to generate rapid variations of acceleration.

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